

HOW COULD THE PROTON TRANSVERSITY BE MEASURED

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The perspectives of two new nonstandard methods of transversal quark polarization measurement are considered: the jet handedness and the so-called "Collins effect" due to spin dependent T-odd fragmentation function responsible for the left-right asymmetry in fragmenting of transversally polarized quarks. Recent experimental indications in favor of these effects are observed:

1. The correlation of the T-odd one-particle fragmentation functions found by DELPHI in $Z \rightarrow 2$ -jet decay. Integrated over the fraction of longitudinal and transversal momenta, this correlation is of 1.6% order, which means order of 13% for the analyzing power.

2. A rather large ($\approx 10\%$) handedness transversal to the production plane observed in the diffractive production of $(\pi^- \pi^+ \pi^-)$ triples from nuclei by the 40 GeV/c π^- -beam. It shows a clear dynamic origin and resembles the single spin asymmetry behavior.

All this makes us hope to use these effects in polarized DIS experiments for transversity measurement. The first estimation of transversity was done by using the azimuthal asymmetry in semi-inclusive DIS recently measured by HERMES and SMC.

1 Introduction

My talk concerns recent progress in the possibility of transverse quark polarization measurement. This is interesting in many aspects, and one of the most important of them is quarks transversity distribution in proton $h_1(x)$ measurement. Let me recall that there are three most important (twist-2) parton distribution functions (PDF) in a nucleon: a non-polarized distribution function $f_1(x)$, longitudinal spin distribution $g_1(x)$ and transversal spin distribution $h_1(x)$. The first two have been more or less successfully measured experimentally in classical deep inelastic scattering (DIS) experiments, but the measurement of the last one is especially difficult since it belongs to the class of the so-called helicity odd structure functions and can not be seen there. To do this, one needs to know the transversal polarization of a quark scattered from a transversally polarized target.

There are several ways to do this:

1. To measure the polarization of a self-analyzing hadron into which the quark fragmentizes in a semi-inclusive DIS, e.g. Λ -hyperon [1]. The drawback of this method, however, is a rather low rate of quark fragmentation into Λ -particle ($\approx 2\%$) and especially that it is mostly sensitive to s -quark polarization.
2. To measure a spin-dependent T-odd parton fragmentation function (PFF) [2, 3, 4] responsible for the left-right asymmetry in fragmentation of a transversally polarized quark with respect to quark momentum-spin plane. (The so-called "Collins asymmetry" [5].)

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3. To measure the transversal handedness in multiparticle parton fragmentation [6], i.e. the correlation of quark spin 4-vector s_μ and particle momenta k_ν , $\epsilon_{\mu\nu\sigma\rho}s^\mu k_1^\nu k_2^\sigma k^\rho$ ($k = k_1 + k_2 + k_3 + \dots$).

The last two methods are comparatively new, and only the last years some experimental indications the the T-odd PFF and the transversal handedness have appeared [7, 8, 9]. Last PRAHA-SPIN Conference I have presented details of these experiments [10]. Now I shortly repeat the result of T-odd PFF measurements (Sect. 2) and concentrates on its application for estimation of the proton transversity distribution (Sect. 3), using the recently measured azimuthal asymmetry in semi-inclusive DIS. Sect. 4 is reserved for conclusions.

2 T-odd quark fragmentation function

The transfer of nucleon polarization to quarks is investigated in deep-inelastic polarized lepton – polarized nucleon scattering experiments [11]. The corresponding nucleon spin structure functions for the longitudinal spin distribution g_1 and transversal spin distribution h_1 for a proton are well known. The *inverse* process, the spin transfer from partons to a final hadron, is also of fundamental interest. Analogies of f_1 , g_1 and h_1 are functions D_1 , G_1 and H_1 , which describe the fragmentation of a non-polarized quark into a non-polarized hadron and a longitudinally or transversely polarized quark into a longitudinally or transversely polarized hadron, respectively ¹⁾.

These fragmentation functions are integrated over the transverse momentum \mathbf{k}_T of a quark with respect to a hadron. With \mathbf{k}_T taken into account, new possibilities arise. Using the Lorentz- and P-invariance one can write, in the leading twist approximation, 8 independent spin structures [2, 3]. Most spectacularly it is seen in the helicity basis where one can build 8 twist-2 combinations, linear in spin matrices of the quark and hadron $\boldsymbol{\sigma}$, \mathbf{S} with momenta \mathbf{k} , \mathbf{P} . Especially interesting is a new T-odd and helicity even structure that describes a left-right asymmetry in the fragmentation of a transversely polarized quark: $H_1^\perp \boldsymbol{\sigma}(\mathbf{P} \times \mathbf{k}_T)/P\langle k_T \rangle$, where the coefficient H_1^\perp is a function of the longitudinal momentum fraction z , quark transversal momentum k_T^2 and $\langle k_T \rangle$ is an average transverse momentum.

In the case of fragmentation to a non-polarized or a zero spin hadron, not only D_1 but also the H_1^\perp term will survive. Together with its analogies in distribution functions f_1 and h_1^\perp , this opens a unique chance of doing spin physics with non-polarized or zero spin hadrons! In particular, since the H_1^\perp term is helicity-odd, it makes possible to measure the proton transversity distribution h_1 in semi-inclusive DIS from a transversely polarized target by measuring the left-right asymmetry of forward produced pions (see [4, 12] and references therein).

The problem is that, first, this function is completely unknown both theoretically and experimentally and should be measured independently. Second, the function H_1^\perp is the so-called T-odd fragmentation function: under the naive time reversal \mathbf{P} , \mathbf{k}_T , \mathbf{S} and $\boldsymbol{\sigma}$ change sign, which demands a purely imaginary (or zero) H_1^\perp

¹⁾ We use the notation of the work [2, 3, 4].

in the contradiction with hermiticity. This, however, does not mean the break of T-invariance but rather the presence of an interference term of different channels in forming the final state with different phase shifts, like in the case of single spin asymmetry phenomena [13]. A simple model for this function could be found in [5]. It was also conjectured [14] that the final state phase shift can be averaged to zero for a single hadron fragmentation upon summing over unobserved states X . Thus, the situation here is far from being clear.

Meanwhile, the data collected by DELPHI (and other LEP experiments) give a unique possibility to measure the function H_1^\perp . The point is that despite the fact that the transverse polarization of a quark (an antiquark) in Z^0 decay is very small ($\mathcal{O}(\hat{\mathbb{I}}_\Pi/\mathcal{M}_Z)$), there is a nontrivial correlation between transverse polarizations of a quark and an antiquark in the Standard Model: $C_{TT}^{q\bar{q}} = (v_q^2 - a_q^2)/(v_q^2 + a_q^2)$, which reaches rather high values at Z^0 peak: $C_{TT}^{u,c} \approx -0.74$ and $C_{TT}^{d,s,b} \approx -0.35$. With the production cross section ratio $\sigma_u/\sigma_d = 0.78$ this gives the value $\langle C_{TT} \rangle \approx -0.5$ for the average over flavors.

The spin correlation results in a peculiar azimuthal angle dependence of produced hadrons (the so-called "one-particle Collins asymmetry"), if the T-odd fragmentation function H_1^\perp does exist [5, 15]. The first probe of it was done three years ago [16] by using a limited DELPHI statistics with the result $\langle H_1^\perp/D_1 \rangle \leq 0.3$, as averaged over quark flavors.

A simpler method has been proposed recently by an Amsterdam group [3]. They predict a specific azimuthal asymmetry of a hadron in a jet around the axis in direction of the second hadron in the opposite jet ²⁾:

$$\frac{d\sigma}{d\cos\theta_2 d\phi_1} \propto (1 + \cos^2\theta_2) \cdot \left(1 + \frac{6}{\pi} \left[\frac{H_1^{q\perp}}{D_1^q} \right]^2 C_{TT}^{q\bar{q}} \frac{\sin^2\theta_2}{1 + \cos^2\theta_2} \cos(2\phi_1) \right) \quad (1)$$

where θ_2 is the polar angle of the electron and the second hadron momenta \mathbf{P}_2 , and ϕ_1 is the azimuthal angle counted off the $(\mathbf{P}_2, \mathbf{e}^-)$ -plane. This looks simpler since there is no need to determine the $q\bar{q}$ direction.

This analysis [7] covered the DELPHI data collected from 1991 through 1995. Only the leading particles in each jet of two-jet events was selected both positive and negative. The corrected for acceptance histograms in ϕ_1 for each bin of θ_2 were fitted by the expression ³⁾ $P_0(1 + P_2 \cos 2\phi_1 + P_3 \cos \phi_1)$. The θ_2 -dependence of P_2 in the whole interval of θ_2 was fitted according to Expr. (1) with the result

$$P_2(\theta_2) = -(15.8 \pm 3.4) \frac{\sin^2\theta_2}{1 + \cos^2\theta_2} \text{ppm}$$

The corresponding analyzing power, summed over z and averaged over quark flavors with $\langle C_{TT} \rangle \approx -0.5$ (assuming $H_1^\perp = \sum_H H_1^{\perp,q/H}$ is flavor-independent)

²⁾ We assume the factorized Gaussian form of k_T dependence for $H_1^{q\perp}$ and D_1^q integrated over $|k_T|$.

³⁾ The term with $\cos \phi_1$ is due to the twist-3 contribution of usual one-particle fragmentation, proportional to the k_T/E .

according to Exp. (1) is

$$\left| \frac{\langle H_1^\perp \rangle}{\langle D_1 \rangle} \right| = 12.9 \pm 1.4\% . \quad (2)$$

The systematic errors, however, are by all means larger than the statistical ones and need further investigation.

3 Proton transversity estimation

Recently azimuthal asymmetries in semi-inclusive hadron production on longitudinally (HERMES [17]) and transversally (SMC [18]) polarized targets were reported which together with DELPHI result (2) allows to an estimation for transversity distribution.

The T-odd azimuthal asymmetry in semi inclusive DIS $ep \rightarrow e'\pi^+X$ which HERMES try to measure consist of two sorts of terms (see [4] Eq. (115)): a twist-2 asymmetry $\sin 2\phi_h$ and a twist-3 asymmetry $\sin \phi_h$. The angle ϕ_h here is the azimuthal angle around z -axis in the direction of virtual γ momentum in the parton Breit frame counted from the electron scattering plane. The first asymmetry is proportional to the k_T -dependent transversal quark spin distribution in a longitudinally polarized proton, h_{1L}^\perp , while the second contains two parts: one term is again proportional to h_{1L}^\perp ; and the second, to the twist-3 distribution function h_L .

The experimentally observed ϕ dependence in HERMES data shows no noticeable trace of $\sin 2\phi$ term. Thus, as a crude approximation one can assume a smallness of $h_{1L}^\perp \gg h_L$. For the same reason $h_L = h_1$ (see [4] Eq. (C15,C19)). This open a possibility to measure the proton transversity using the *longitudinally* polarized target.

The asymmetry measured by HERMES

$$A_{OL} = \frac{\int d\phi \sin \phi (d\sigma^+/d\phi)}{P_H^+ \int d\phi (d\sigma^+/d\phi)} - \frac{\int d\phi \sin \phi (d\sigma^-/d\phi)}{P_H^- \int d\phi (d\sigma^-/d\phi)} , \quad (3)$$

where P_H^\pm is the nucleon longitudinal polarization (\pm sign means different spin directions) averaged over transversal momenta (assuming a Gaussian distribution) should reads as ([4] Eq. (115))

$$A_{OL} = \frac{2(2-y)\sqrt{1-y}(\frac{M}{Q}) \sum_a e_a^2 x^2 h_1^a(x) H_1^{\perp a/\pi^+}(z)/z}{(1-y+y^2/2) \sum_a e_a^2 x f_1^a(x) D_1^{a/\pi^+}(z)} \cdot \frac{1}{\sqrt{1 + \langle p_T^2 \rangle / \langle k_T^2 \rangle}} \quad (4)$$

where $\langle p_T^2 \rangle$ and $\langle k_T^2 \rangle$ are mean square of a transversal momenta of quark in the distribution and fragmentation functions.

Averaging separately numerator and denominator over Q^2 , y and z , and taking into account only the u-quark distribution in the proton ($f_1^u(x) \equiv u(x)$) which gives a dominant contribution for the π^+ production and assuming $\langle p_T^2 \rangle = \langle k_T^2 \rangle$, one can obtain for asymmetry (3)

$$A_{OL}(x) = \frac{2.1}{\langle z \rangle \sqrt{2}} \cdot \left[\frac{h_1^u(x)}{u(x)} \right] \cdot \left[\frac{\langle H_1^{\perp u/\pi^+}(z) \rangle}{\langle D_1^{u/\pi^+}(z) \rangle} \right] \cdot x \quad (5)$$

Experimentally [17], $A_{OL}(x)$ for π^+ up to $x = 0.3$ looks like a linear function

$$A_{OL}(x) = (0.23 \pm 0.06)x \quad (6)$$

With $\langle z \rangle = 0.41$ and DELPHI result (2) this gives an estimation for the ratio

$$\frac{h_1^u(x)}{u(x)} = \text{const} = 0.49 \pm 0.18 \quad (7)$$

Assuming the validity of (7) for valence parts in the whole interval of x one could obtain an estimation for the u -quark contribution to the proton tensor charge

$$g_T^u \equiv \int dx \left(h_1^u(x) - h_1^{\bar{u}}(x) \right) = 0.96 \pm 0.36 \quad (8)$$

that is close to the result of the chiral quark-soliton model [19] $g_T^u \approx 1.12$ and to the limit followed from the density matrix positivity constraint at $Q^2 = 2.5 \text{ GeV}^2$ [20] $g_T^u \leq 1.09$.

Concerning the asymmetry observed by SMC [18] on transversely polarized target one can state that it agrees with the result of HERMES.

Really, SMC has observed the azimuthal asymmetry $d\sigma(\phi_c) \propto \text{const} \cdot (1 + a \sin \phi_c)$, where $\phi_c = \phi_h + \phi_S - \pi$ (ϕ_S is the azimuthal angle of the polarization vector) is the so-called Collins angle. The raw asymmetry $a = P_T \cdot f \cdot D_{NN} \cdot A_N$, where P_T , f , and $D_{NN} = 2(1-y)/[1 + (1-y)^2]$ are the target polarization value, the dilution factor and the spin transfer coefficient.

The physical asymmetry A_N averaged over transverse momenta (assuming again a Gaussian form) is given by the expression (see [4] Eq. (116))

$$A_N = \frac{\sum_a e_a^2 x h_1^a(x) H_1^{\perp a/\pi^+}(z)/z}{\sum_a e_a^2 x f_1^a(x) D_1^{a/\pi^+}(z)} \cdot \frac{1}{\sqrt{1 + \langle p_T^2 \rangle / \langle k_T^2 \rangle}} \quad (9)$$

Integration over x and z , and using again the approximation of the u -quark dominance and $\langle p_T^2 \rangle = \langle k_T^2 \rangle$ gives from the experimental value $A_N = 0.11 \pm 0.06$, $\langle z \rangle = 0.45$ and DELPHI result (2)

$$\frac{\langle x h_1^u(x) \rangle}{\langle x u(x) \rangle} = 0.54 \pm 0.35 \quad (10)$$

what in agreement with the HERMES ratio (7).

4 Conclusions

In conclusion, I would like to stress that there are several ways allowing one to measure the transverse quark polarization among which the use of the T-odd PFF looks like the most perspective for future experiments in measuring of transversity, like COMPASS at CERN. I present the first experimental estimation for the

absolute value of analyzing power of the method. Of course, a more accurate measurements of it is necessary. However, even now it allows the first crude estimation of the proton transversity from observed azimuthal asymmetry in semi-inclusive DIS. The most interesting discovery here is a good agreement of transversities obtained from transversally and longitudinally polarized targets due to small contribution of $h_{1L}^\perp(x)$. This allows measuring the transversity in the same experiments as for Δg .

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